Final Report

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"Towards a Multisensor Approach to Improve on Current TRMM Retrievals of Clouds and Precipitation"

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The Tropical Rainfall Measuring Mission (TRMM) was designed to measure tropical rainfall and its variation from a low inclination orbiting satellite. The TRMM payload was carefully chosen to overcome a number of limitations of past satellite observing systems. This payload is predicated on the combination of active and passive observations from the TRMM Precipitation Radar (PR) and TRMM Microwave Imager (TMI) and Visible and Infrared Scanner (VIRS). Our research over the past three years has been devoted to the challenge of developing the most effective way of combining complementary information from these sensors to provide the most consistent estimate of precipitation. We have approached this problem from three directions. The first was to carry out preliminary analysis of passive microwave and infrared data from the TMI and VIRS instruments to understand the character of clear and cloudy skies in the basis defined by polarization and brightness temperature differences. Using this information as a foundation, the properties of two retrieval algorithms were analyzed, one for retrieving ice clouds from VIRS that was developed in parallel with this project and the other for rainfall from the TMI. Finally, the knowledge gleaned from each of these studies, coupled with ancillary data from NWP models and a broadband radiative transfer model, was used to create and algorithm for synthesizing the principal components of the Earth's energy budget from the basic building blocks of the atmosphere, gases, clouds, and precipitation. Principal results from each of these areas of research and their role in the TRMM and climate communities are summarized in the sections which follow.

1 Atmospheric Properties

As a first step in preparing for the use of TMI data in combined algorithms, we examined the properties of TMI polarization signatures in clear and cloudy skies. As part of this

research an accurate yet computationally efficient discrimination-scheme based on multiple VIRS channels has been developed to distinguish between clear and cloudy pixels. Making use of this discrimination procedure, a database of clear and cloudy sky radiances and TMI polarization differences has been created from a large volume of TRMM data. This database was then employed to study the relationship between TMI polarization differences and the properties of clouds and precipitation as indicated by alternate means, such as integrated reflectivity from the TRMM PR. This study, while shorter in duration than other aspects of this research, has provided useful insights into the properties of clouds and precipitation in a number of TRMM observations. These results implicitly formed the foundation of all future endeavors related to the project.

2   Toward a Combined TMI-PR Rainfall Algorithm

The conclusions of the previous section clearly demonstrate that radiances in different regions of the electromagnetic spectrum, infrared and microwave wavelengths in this case, provide information regarding different aspects of the atmosphere. While microwave radiation is sensitive to precipitation-sized particles, atmospheric signatures at infrared wavelengths are primarily dominated by clouds. In addition to the TMI and VIRS radiometers, TRMM also carries the first space-borne precipitation radar and it is of great interest to further investigate the potential for combining active and passive observations in rainfall estimation algorithms. Since it is possible to attribute radar reflectivity observations to particular levels in the atmosphere, PR data should, in principle, carry with it substantially greater vertical structure information than passive observations which derive from integrals over the entire atmosphere.

In order to better understand the complementary nature of active and passive observations a series of in-depth studies of TMI-based rainfall retrievals have been conducted as part of this research including detailed investigation of the sensitivity of each TMI channel to rainfall, analysis of TMI weighting functions for a variety of rainrates, and a detailed study of the information content of the TMI measurements. Through the use of a conceptually simple analysis of the principal components of the TMI measurements, we have estimated the number of independent pieces of information contained in the data as a function of rainfall rate. The results suggest that the retrievable range of rainrates can be broken down into three categories:

- Low rainrates between 0.25 and 6 mm h^{-1} (1.5 and 4.5 mm h^{-1} over land). Here the instrument is most sensitive to the rain nearest the surface but exhibits slight sensitivity to the cloud

- Moderate rainrates between 6 and 22 mm h^{-1} (4.5 and 18 mm h^{-1} over land). This is the ideal range of rainfall for algorithms which estimate surface rainfall and cloud profiles simultaneously since the instrument is sensitive to both the surface as well as a number of layers within the cloud.

- High rainrates above 22 mm h^{-1} (18 mm h^{-1} over land). Intense rainfall and the large amounts of ice which often overly it prevent all TMI channels from viewing the surface. At these rainrates, limited cloud profiling is possible but the surface rainrate can only be inferred from the liquid and ice water at upper levels.

In the low rainrate region, cloud profiles impact the retrieval but the TMI instrument is likely not sensitive enough to retrieve them without the aid of additional information. This is the region in which all TMI-only rainfall retrieval algorithms will suffer the largest uncertainties due to cloud profile effects regardless of whether or not they attempt to retrieve cloud structure. At moderate rainrates more sophisticated algorithms should perform more accurately since the TMI channels carry information necessary to retrieve a full rainfall profile as well as an estimate of the column ice water content in addition to the surface rainrate. Finally, in heavy rain, the TMI does not directly sense the lowest levels of the atmosphere or surface at all. Surface rainfall estimates under such conditions require an explicit relationship between hydrometeor concentration and size within the cloud and rainfall at the surface.

In addition we have stripped the TMI-based Goddard Profiling (GPROF) Algorithm (described in Kummerow and Giglio (1994) (*J. Appl. Meteor.* **33**, pp. 3-18)) to its bare-bones and performed a detailed analysis of its accuracy both in its present form, using only TMI radiances, and after including PR reflectivity profiles. The resulting error model provides a rigorous estimate of the uncertainty in all retrieved parameters as well as a breakdown of this uncertainty into two components attributable to an imperfect database and modeling and measurement uncertainties, respectively. This error information is critical for algorithm development, model validation, and, in particular, in variational data assimilation where the relative accuracy of the observations and the background forecast determines how much the latter is modified in the assimilation process.

Using the error model, uncertainties in the TMI instantaneous surface rainfall product (2A12) have been found to range from 40 to 60 percent in rainfall up to 20 mm h^{-1} as indicated in Figure 1. In heavier rain, uncertainties rapidly increase due to heavy attenuation in all TMI channels which requires surface rainfall to be inferred solely from the non-unique relationship between surface rainrate and the ice scattering signature in the strongly coupled 37 and 85 GHz brightness temperatures. In light rain, the fact that the database attempts to approximate nature's infinite cloud probability density function by a finite set of realizations and the inherent inability of the TMI brightness temperatures to completely distinguish

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between all cloud profiles in the database dominate retrieval uncertainties. Between 4 and 10 mm h^{-1} both error components are comparable while measurement and model uncertainties dominate in heavier rainfall.
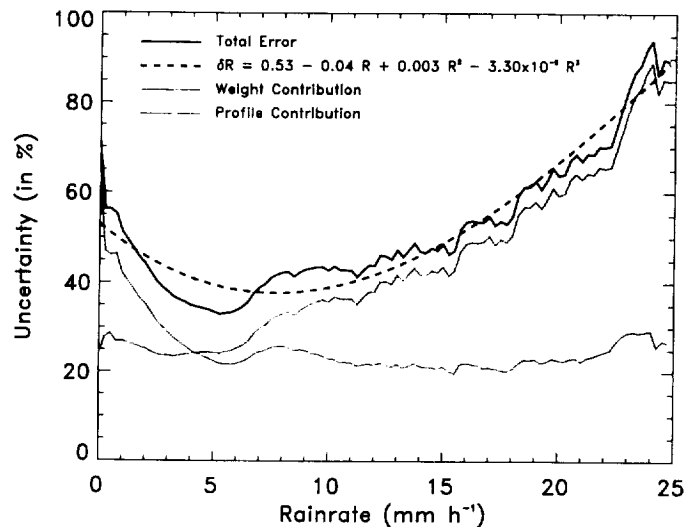

Figure 1: Cloud database and weight components of uncertainty in retrieved surface rainfall for all oceanic pixels in 10 TRMM orbits. Unless otherwise noted, all subsequent figures display statistics corresponding to the same subset of oceanic pixels.

The value of adding vertical structure information contained in the PR data to the GPROF algorithm has also been investigated. Preliminary attempts to incorporate radar reflectivity data to reduce profile database uncertainties show promise but can lead to a compensating increase in the modeling and measurement error component. This research highlights the need for further studying sources of systematic error in the cloud database such as errors in cloud microphysical assumptions, beamfilling errors, or biases in the radiative transfer calculations used to simulate brightness temperatures for each profile. In addition to this TRMM application, the error model can be applied to estimate uncertainties in any Bayesian Monte Carlo retrieval algorithm.

The concepts that have emerged from these studies are, at present, being used to form the foundation for a combined radar-radiometer algorithm for TRMM and its proposed successor the Global Precipitation Misson (GPM). Through recent developments in the planning stages of the next generation of rainfall algorithms, the central role of a rigorous error model has become apparent. We anticipate that the results of this research will play an integral role in future algorithms and in designing field campaigns to validate them.

3 Ice Cloud Retrievals from VIRS

Following up on the results of Section 1, an optimal estimation algorithm to estimate the microphysical properties of thin cirrus clouds from the 10.8 and 12 μm channels on VIRS has been developed as part of this research. The optimal estimation framework provides error diagnostics for all retrieved parameters often lacking in other retrievals and facilitates addition of information from complementary sensors into the retrieval. Ackerman et al (1990) (*Monthly Weather Review* 118, pp. 2377-2388) for example, show that 8.5 μm radiances can be used in conjunction with those at window wavelengths to distinguish between water and ice clouds. Such information can easily be added to the algorithm providing a liquid cloud mask, increasing its speed and accuracy when applied on global scales. Furthermore, the algorithm has been constructed in such a way as to include explicit cloud boundary information which is found to significantly reduce the biases inherent in traditional implementations of the of the approach. Figure 2 provides an example of retrieved optical depth, effective radius, and cloud emitting temperature for a segment of a TRMM orbit. Expected uncertainties in each of the algorithm products, provided by built-in error diagnostics, are summarized in Figure 3. Errors in retrieved optical depth range from 20 to 40 % while uncertainties in effective radius estimates typically lie between 60 and 100 % thus optical depth is retrieved to much higher precision than effective radius.

Synthetic retrievals indicate that the more accurate the estimate of cloud emitting temperature, T_c, the higher the probability of obtaining an accurate retrieval given a measurement with random error. Retrieval errors provided by the optimal estimation approach suggest that optical depth is determined significantly more accurately than effective radius, an artifact of the sensitivity of the forward model physics to each of these parameters. For an error in cloud temperature of 2 K, characteristic of lidar-based estimates of cloud emitting temperature, the average error in retrieved optical depth and effective radius are $\sim$15 and $\sim$60 percent, respectively, significantly better than retrievals performed with less accurate cloud temperature information. Application of the algorithm to coincident measurements of infrared radiances from TRMM and cloud boundary measurements from the ARM Nauru site confirms these results. Differences between retrievals using accurate cloud boundary information and those performed with a less accurate climatological estimate of T_c were on the order of 10 and 30 percent for optical depth and effective radius, respectively, while retrieval uncertainties were generally much larger in the absence of cloud boundary information. Furthermore, cloud boundary information proves invaluable in eliminating the potential for ambiguities in cases where the satellite field of view observed either multiple cloud layers or water clouds.

It is anticipated that these results will play an important role in the development of multi-sensor algorithms for a number of future NASA-sponsored missions. The combination
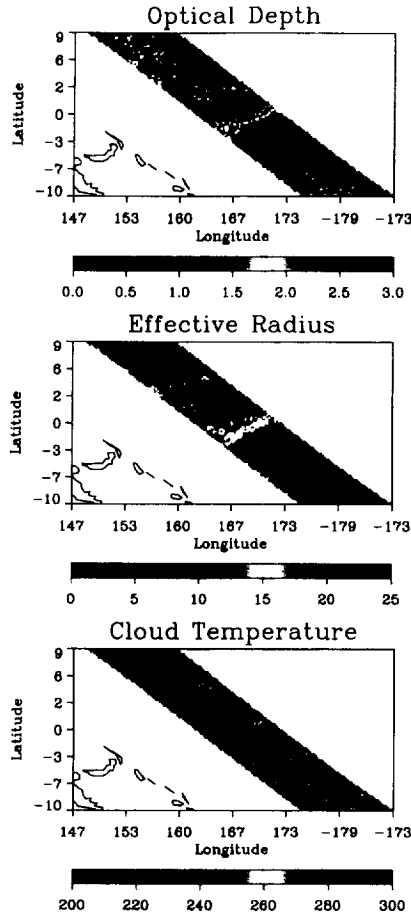
Figure 2: Retrieved optical depth, effective radius (in μm), and cloud emitting temperature (in K) for a sample segment of a TRMM orbit. Gray pixels represent areas of optically thick, precipitating cloud.

of active and passive measurements required for the implementation of such algorithms will soon be available on a global scale with coincident measurements from the Earth Observing System (EOS) Aqua, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), and CloudSat satellites which are scheduled to fly in formation in early 2004. Infrared radiances from the Moderate Resolution Imaging Spectrometer (MODIS) instrument aboard Aqua, for example, can be combined with lidar data from CALIPSO, or, equivalently, cloud radar data from the 94 GHz CloudSat Cloud Profiling Radar (CPR), to retrieve thin cirrus clouds globally.
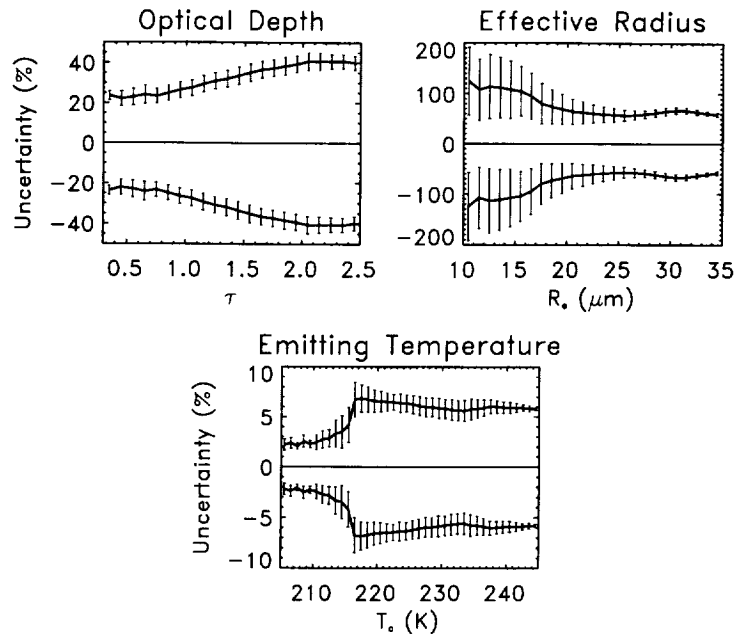
Figure 3: Estimated uncertainty in ice cloud optical depth, effective radius, and cloud emitting temperature. Solid lines correspond to mean uncertainties in all retrievals over ten TRMM orbits while error bars represent the standard deviation about that mean for all appropriate pixels in the sample.

4 Application to Climate Research

Over the course of the final year, our research has expanded to apply TRMM data to study the role of clouds and precipitation in the climate. Maintaining the multi-sensor philosophy adopted in the other aspects of this research, a complete algorithm has been developed for estimating the tropical energy budget and hydrologic cycle from TRMM observations consolidating the complimentary cloud and precipitation information from the VIRS and TMI instruments aboard TRMM.

The technique makes use of cloud and precipitation information from TRMM to estimate the principal components of the tropical energy budget and to examine the mechanisms by which clouds and precipitation modify it. Three distinct retrieval algorithms, two of which were developed under this funding, are employed to determine the three-dimensional structure of cloud and precipitation in the tropical atmosphere. The first is the GPROF algorithm which retrieves cloud and precipitation profiles from passive microwave observations from the TMI. The second algorithm applies a different technique to the TMI radiances to derive estimates of non-precipitating liquid cloud and the third, described in Section 3, makes use

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of VIRS infrared radiances to infer ice cloud optical properties in non-precipitating regions. The resulting representation of the three-dimensional structure of cloud and precipitation in the tropical atmosphere is then used as input to a broadband radiative transfer model to derive profiles of short- and longwave fluxes. These flux profiles are composited to present a TRMM-based estimate of the short-term tropical energy budget for oceanic regions over the month of February 1998, illustrated in Figure 4.
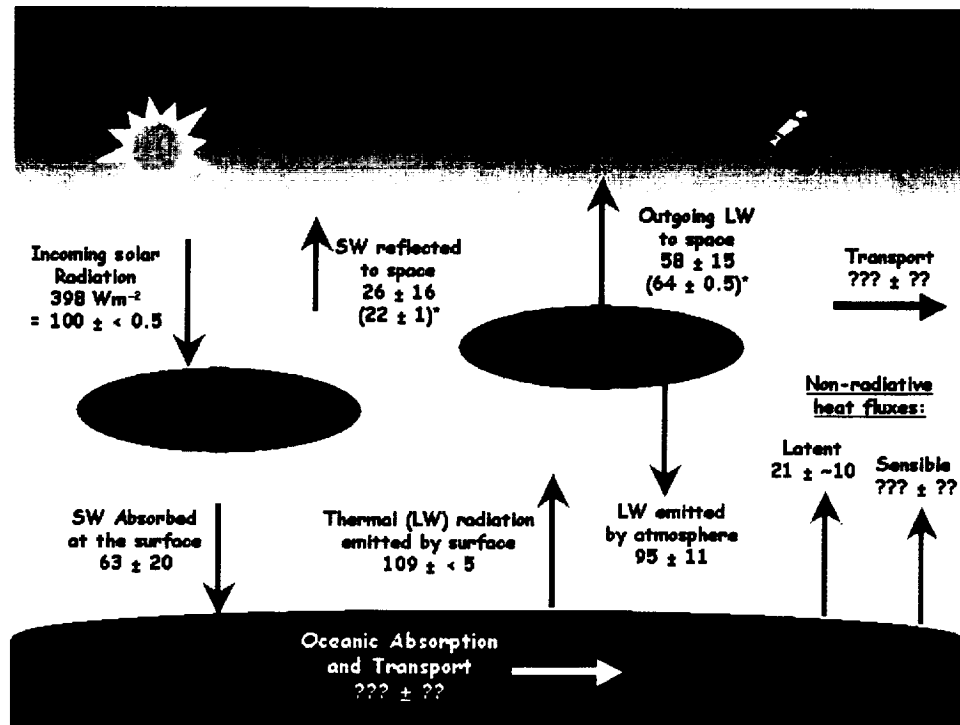

Figure 4: Principal components of the tropical oceanic energy budget for February, 1998. All fluxes have been normalized by the mean solar insolation at the top of the atmosphere, 407 Wm^{-2}. Corresponding CERES data is provided in parentheses for comparison.

On average, over this period, the tropical atmosphere absorbs 51 Wm^{-2} or 13 % of the 393 Wm^{-2} of solar radiation it receives. A further 112 Wm^{-2} is reflected by atmospheric particles, clouds, and the surface, leaving 230 Wm^{-2} to be absorbed by the ocean. At thermal wavelengths, it is found that the ocean emits 436 Wm^{-2} of energy to the atmosphere while the atmosphere emits a total of 639 Wm^{-2} units, 407 Wm^{-2} downward toward the surface and 231 Wm^{-2} to space. Accounting for latent heat release which amounts to an exchange of 82 Wm^{-2} of energy between the surface and atmosphere, the results imply a deficit of 70 Wm^{-2} of energy in the atmosphere and a surplus of 121 Wm^{-2} at the Earth's surface. The implied net gain of 51 Wm^{-2} in the Earth-atmosphere system is consistent with a difference between the incoming solar radiation and emitted thermal radiation at the top of

the atmosphere. It is speculated that these imbalances are largely accounted for by sensible heating, meridional energy transport, and absorption and transport of energy in the ocean. Finally, on average for the month of February 1998, the tropical atmosphere cools at -1 Kday^{-1} and experiences a net cloud forcing of -10 Wm^{-2} at TOA and -22 Wm^{-2} at the surface.

As part of this research, concerted effort has been made to rigorously characterize the uncertainties in all aspects of the approach. In the absence of additional tuning or constraints, the procedure provides monthly-mean estimates of column radiative heating accurate to $\sim$ 30 % and cloud radiative forcing with accuracies ranging from approximately 40 % for raining pixels to 75 % in non-precipitating clouds. The dominant source of uncertainty in both the retrieval and radiative transfer models is a lack of vertical cloud boundary information inherent in the passive measurements. These results highlight the need for future algorithms to look toward making use of synergies between active and passive observations to simultaneously retrieve cloud and precipitation optical properties and their vertical distribution and ensure consistency between a wider variety of information sources.

The technique developed in this research provides a complete approach for generating tropic-wide (and ultimately global) estimates of the components of the energy budget using explicit cloud and precipitation information from spaceborne observations. In the future, the results can be applied to study short term climate variability through investigations of perturbations to the radiation balance induced by changes in the distributions of water vapor, cloud, and precipitation on short to moderate timescales affording us the opportunity to quantify important relationships between the hydrologic cycle and the Earth's energy budget using TRMM data.

5 Summary

In summary, the research funded under NASA TRMM Research Grant NAG5-7719 evolved in two primary directions: (1) an investigation of the synergies between measurements from the different instruments aboard the TRMM satellite toward the goal of the development of a combined algorithm as originally proposed, and (2) the construction and evaluation of new techniques for estimating the principal components of the Earth's energy budget from TRMM observations. The research topics covered include

- Radiative signatures of clear and cloudy skies have been documented.

- Information content of the TMI for retrieving rainfall over both land and ocean backgrounds has been quantified.

- A complete algorithm for retrieving ice cloud optical propeties from the VIRS instrument cast in the optimal-estimation framework has been developed.

- Uncertainties in emission-based retrievals of ice cloud optical properties and the impact of explicit cloud boundary information on such retrievals have been quantified.

- An error model for Bayesian Monte Carlo retrieval algorithms has evolved and used to analyze the GPROF algorithm yielding a number of results that will shape future rainfall algorithms such as those being developed for GPM.

- An algorithm for determining the principal components of the Earth's radiation budget has been developed laying the foundation for an experimental energy budget product to be included in future reprocessing.

A list of refereed publications and a PhD dissertation that have emerged from this research is provided below. In addition, elements of this work have been the focus of numerous talks and poster presentations over the past three years.

Publications Supported Through NAG5-7719

Cooper, S. J., T. S. L'Ecuyer, and G. L. Stephens, 2002: "The Impact of Explicit Cloud Boundary Information on Ice Cloud Microphysical Property Retrievals from Infrared Radiances", submitted to *J. Geophys. Res.*.

L'Ecuyer, T. S. and G. L. Stephens, 2002: "The Tropical Oceanic Energy Budget from the TRMM Perspective. Part I: Algorithm and Uncertainties", in preparation.

L'Ecuyer, T. S. and G. L. Stephens, 2002: "The Tropical Oceanic Energy Budget from the TRMM Perspective. Part II: Climate Applications", in preparation.

Stephens G. L., P. J. Webster, R. H. Johnson, R. Engelen and T. S. L'Ecuyer, 2002: "On the mutual regulation of the Tropical Hydrological Cycle and Tropical Sea Surface Temperatures. Part I: Observational evidence for the humidistat feedback", in preparation.

L'Ecuyer, T. S. and G. L. Stephens, 2002: "An Uncertainty Model for Bayesian Monte Carlo Retrieval Algorithms: Application to the TRMM Observing System", *Q. J. R. Meteorol. Soc.*, in press.

L'Ecuyer, T. S., 2001. "Uncertainties in Space-based Estimates of Clouds and Precipitation: Implications for Deriving Global Diabatic Heating", *PhD Dissertation*, Colorado State University, Fort Collins, CO, USA.